Tilt Rotor Aeroacoustic Model Project

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Summary

A new tiltrotor aeroacoustic research facility, the Tilt Rotor Aeroacoustic Model (TRAM), is being developed by NASA and the U. S. Army. The TRAM Project will enable new insights into the fundamental aeroacoustics of proprotors and tiltrotor aircraft, leading to improved acoustic prediction methodologies and noise reduction techniques. An overview of NASA's goals in understanding and reducing the technology barriers for civil tiltrotor aircraft is provided as well as a description of how TRAM will support these goals. TRAM is capable of being configured as an isolated rotor or as a complete full-span dual rotor aircraft model. The TRAM test stands and their modular, compatible sub-systems are described in detail. Sample results from an isolated rotor test recently completed at the Duits-Nederlandse Windtunnel are presented. The current status of the full-span model development is described.

Nomenclature

C_T Rotor thrust coefficient

M_{tip} Hover tip Mach number

α_S Rotor shaft angle, deg

θ Rotor collective, deg

μ Rotor advance ratio

ψ Rotor azimuth angle, deg

Presented at the Confederation of European Aerospace Societies (CEAS) Forum on Aeroacoustics of Rotorcraft and Propellers, Rome, Italy, June 9-11, 1999.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Tilt Rotor Aeroacoustic Model Project**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NASA Ames Research Center,Moffett Field,CA,94035**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**21**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Introduction

The purpose of this paper is to describe a new tiltrotor aeroacoustic research facility: the Tilt Rotor Aeroacoustic Model (TRAM). The paper will provide a detailed description of the two TRAM test stand configurations and their sub-systems, provide a sample of recently acquired isolated rotor results, and describe the current state of the full-span model development and its future research potential.

The U. S. Government has long held an interest in developing high-speed rotorcraft for both military and civilian applications and has studied numerous concepts since the 1950's. Starting with the first successful in-flight conversion by the XV-3 in 1958 and followed by the very successful XV-15 flight research vehicle (1970's) and the V-22 Osprey development (late 80's and 90's), the tiltrotor concept has clearly established itself as a viable high-speed rotorcraft design. Figure 1 shows these three aircraft in flight.

Figure 1. The XV-3, XV-15 and V-22 Osprey tiltrotor aircraft

Over the past two decades, as V-22 Osprey development progressed, many have become convinced that tiltrotor aircraft have civil transport applications. The Civil Tiltrotor Development Advisory Committee (CTRDAC), Ref. 1, studied the technical feasibility and financial viability of developing a civil tiltrotor aircraft. In their report to Congress, the Committee concluded that the civil tiltrotor concept is technically feasible, a market exists and the civil tiltrotor has the potential of relieving congestion at major airports. In addition, the report describes some of the barriers to be overcome for successful implementation of a civil tiltrotor. These include development of infrastructure, understanding safety and community acceptance requirements, integration into the air traffic control system and economics. NASA, through the Advanced Subsonic Transport and the Aviation Systems Capacity programs, initiated the Short Haul (Civil Tiltrotor) [SH(CT)] program to address the concern about tiltrotor noise, as well as operating efficiency and safety, for civil applications.

The SH(CT) program quickly recognized that reducing noise would be fundamental to passenger and community acceptance of the civil tiltrotor. Therefore, studying tiltrotor aeroacoustics in order to understand tiltrotor noise mechanisms and developing advanced low-noise rotors has been a high priority within the SH(CT) program.

As described in Ref. 2, the SH(CT) program outlines three areas for tiltrotor noise reduction: noise abatement, noise reduction through innovative proprotor designs (including active rotor control strategies), and improved noise prediction methodologies. Reference 2 also provides an overview of tiltrotor research conducted in these three areas through 1996.

Need for Tiltrotor Aeroacoustic Wind Tunnel Testing

For over 50 years the helicopter has evolved into a highly successful vehicle fulfilling a variety of useful VTOL missions in both civil and military air transport. Throughout this period, much effort has been spent studying helicopter noise mechanisms in order to devise techniques for reducing noise generated by this class of rotorcraft. Despite many years of investigation and numerous successes, rotorcraft aeroacoustic research continues to be a challenging field. Tiltrotors, in addition to being more complex aerodynamically (and hence, aeroacoustically), have had relatively less acoustic research effort than conventional helicopters. Although tiltrotor and helicopter rotors have common noise sources (such as blade-vortex interaction noise, high-speed impulsive noise and broadband noise), the aerodynamics of a tiltrotor blade can be vastly different than a conventional helicopter blade.

Compared to a helicopter blade, tiltrotor blades have thicker airfoils with higher built-in twist and operate at higher tip speeds with higher loading. These differences result in very different blade load distributions. Hence, existing analytical and empirical models developed for helicopter rotors do not necessarily apply to tiltrotors. In particular, the wake geometry models for helicopters are inadequate for tiltrotor wake systems. In descent conditions, tiltrotor blades can undergo negative tip loading over a substantial region of the rotor disk compared with conventional helicopter blades. The negative tip loading causes dual vortices, of opposite sign, to be shed from a single blade. The dual vortices greatly complicate the wake geometry and present a challenge to the analyst trying to model the wake. In addition, the dual-rotor arrangement over the wing results in aerodynamic interaction between the rotor and wing/fuselage. This interaction is evident during hover where the downwash from the rotors creates a download on the wing and a vertical inboard upwash and subsequent reingestion of a portion of the rotor wake into the disk. This phenomenon is known as the ‘fountain effect.’ Finally, tiltrotors operate in a wide range of conditions compared with helicopters because the rotor position relative to the fuselage can vary over 90 deg - from hover to propeller mode.

For all of the above reasons, less is understood about the aeroacoustics of tiltrotors than helicopters. Improved understanding of tiltrotor aeroacoustics requires primarily two key types of experimental data: blade airloads and rotor wake measurements. This data will be essential to validating acoustic prediction codes.

NASA is currently developing a new generation of aeroacoustic and aeromechanics prediction tools, some of which are uniquely tailored for tiltrotors. In order to validate this new predictive capability it is important to acquire a fundamental database of tiltrotor acoustics and aerodynamics. Further, because of unique configuration of the rotors in relation to the wing and fuselage, it is important to not only measure isolated rotor characteristics, but full-span dual-rotor airframe representative data as well.

TRAM Program Overview

The TRAM program was initiated to provide the data necessary to confirm performance and aeroacoustic prediction methodologies and to investigate advanced low-noise tiltrotor technologies. To accomplish these noise reduction goals, wind tunnel testing of moderate- to large-scale tiltrotor models is required.

Primary TRAM program goals are:

- Use the V-22 aircraft as the baseline for development of a high fidelity, small-scale aeroacoustic model. Fundamental to this design is a pressure-instrumented rotor having kinematic and dynamic similarity to the V-22 aircraft.

- Develop a hardware-compatible isolated rotor and full-span (dual-rotor, complete airframe representation) test stand to study important interactional aeroacoustic phenomena. The two TRAM configurations are not independent test stands, but share common modular sub-assemblies.

- Incorporate into the test stands (and associated auxiliary test equipment) a comprehensive suite of high-precision, high-bandwidth instrumentation to adequately characterize tiltrotor aerodynamics and acoustics. This includes the acquisition of unsteady rotor airloads, wing static airloads, acoustics, rotor and airframe performance data, rotor wake vortex trajectory and vortex velocity measurements.

The TRAM baseline rotors and airframe are based on a 1/4-scale V-22 Osprey tiltrotor aircraft. Selection of the V-22 as a baseline was dictated by two primary considerations. First, the gross weight of the V-22 is close to the proposed 40-passenger civil tiltrotor studied by the CTRDAC and others. Therefore, the civil tiltrotor proprotor performance characteristics will be similar to those of the V-22. Second, as the first production tiltrotor aircraft, many V-22's will be flying and providing valuable operational data in the years ahead. This will create opportunities for comparisons between wind tunnel test results and full-scale flight vehicle data.

The 1/4-scale model size was selected with consideration of the test section size of the two facilities where TRAM would primarily be tested. For isolated rotor testing, the TRAM was intended to be tested in the open-jet test section of the Duits-Nederlandse Windtunnel and, for the full-span dual rotor model, the 40- by 80-Foot Test Section of the National Full-Scale Aerodynamic Complex (NFAC). The next section describes the TRAM model.

Tilt Rotor Aeroacoustic Model Description

TRAM is configured as either an isolated rotor model or a full-span dual rotor aircraft model. Figures 2 and 3 show the isolated rotor and full-span TRAM configurations respectively.

Figure 2. Isolated rotor TRAM configuration

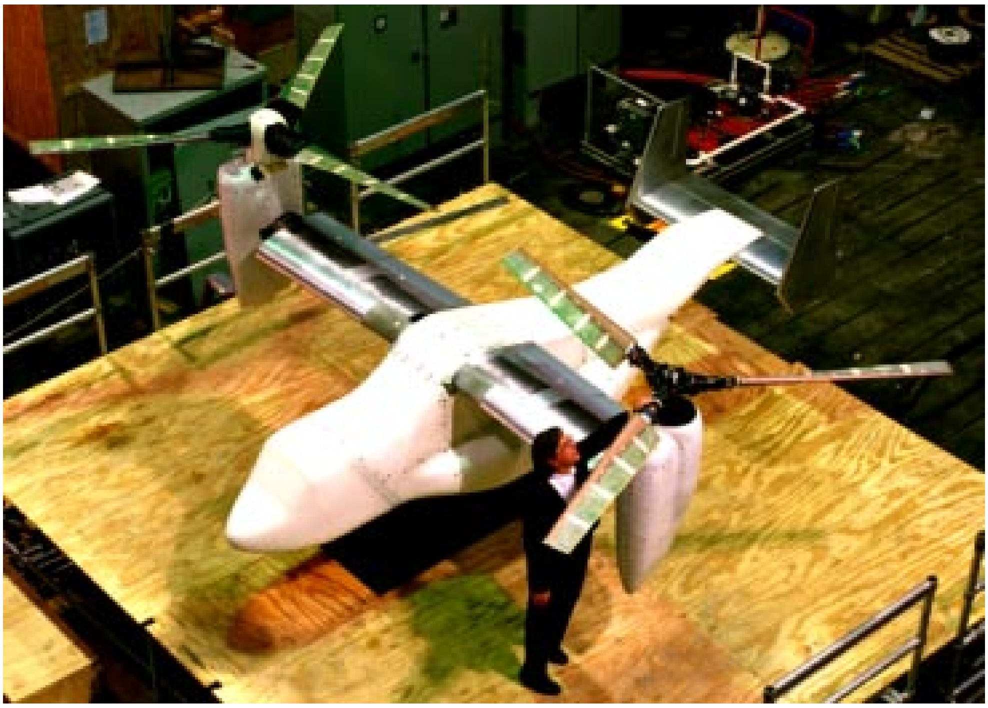


Figure 3. Full-span TRAM configuration

The TRAM can be configured as an isolated rotor or dual-rotor full-span aircraft model. This makes it uniquely suited for identifying and studying tiltrotor aerodynamics and acoustics in a rigorous experimental manner. The drive train, nacelle assembly, hub and rotor components from the isolated rotor model are also used to make up the right-hand rotor and nacelle assembly on the full-span model. Each rotor is powered by an electric motor designed to deliver up to 300 hp at 1588 rpm.

The right hand rotor has a set of pressure-instrumented blades and a set of strain-gauged blades, the left-hand rotor blades have only strain gauge instrumentation. The TRAM blades and hub

retention system are fabricated with composite materials and are structurally tailored to match fundamental frequencies of the full-scale aircraft. The hub and control system is kinematically similar to the full-scale aircraft. Both left-hand and right-hand rotor forces and moments are measured with strain-gauged balances located in each pylon assembly. The overall aerodynamic loads on the full-span model are measured with a strain-gauged balance located in the fuselage.

One of the TRAM characteristics that provides tremendous research capability for developing a tiltrotor aeroacoustics database, together with its data acquisition and recording system, is its ability to simultaneously acquire blade pressure and microphone data at extremely high rates. TRAM acquires 150 blade pressure measurements and up to 20 microphone measurements at 2048 samples per rotor revolution. Since the TRAM rotor spins at 26.5 revs per second, the data acquisition rate is more than 54,000 samples per second per channel. A state-of-the-art signal conditioning and data acquisition system was specifically designed to accommodate TRAM data rate requirements.

A detailed description of both the isolated rotor model and full-span model and their systems is provided in the Appendix.

TRAM Isolated Rotor Testing

In order to gain a further understanding of tiltrotor aeroacoustics, NASA and the U. S. Army conducted the TRAM isolated rotor test program in the Duits-Nederlandse Windtunnel (DNW). This isolated rotor test was the first comprehensive aeroacoustic test for a tiltrotor in forward flight. Rotor noise, rotor performance, rotor airloads, wake geometry and wake velocities were measured. An overview of TRAM DNW isolated rotor testing is provided in Ref. 3. A description of the DNW and its rotary-wing test capability is found in Ref. 4. A short summary of this test program is provided below.

The TRAM isolated proprotor was tested in the 8-by-6 meter open-jet test section of the DNW (Fig. 4). Two tunnel entries were conducted with the TRAM isolated rotor test stand and the 1/4-scale V-22 rotor. The first tunnel entry, in December 1997, focused on test stand risk-reduction and envelope expansion. The second entry in April-May 1998 was devoted to acquiring a high quality isolated rotor aeroacoustic database.

Figure 4. TRAM isolated rotor configuration and the DNW acoustic traverse

The TRAM DNW test focused primarily on low-speed helicopter-mode test conditions. Test objectives were, in order of importance:

- Perform detailed acoustic survey of blade vortex interaction (BVI) phenomena in helicopter-mode descent including rotor noise trends as a function of advance ratio, rotor shaft angle, tip Mach number and thrust coefficient.

- Acquire broadband noise data in hover and low-speed helicopter-mode flight

- Acquire performance, airloads, wake vortex and trailed tip vortex velocity measurements for helicopter-mode flight.

- Obtain proprotor airplane-mode performance and airloads measurements up to the maximum DNW open test-section tunnel speed, $\mu = 0.375$ at $M_{tip} = 0.59$.

Because of time and load limit constraints, transition flight ($-15 < \alpha_S < -75$ deg) measurements were not made. Data were acquired to meet all other test objectives.

The 1/4-scale V-22 proprotor was tested at a reduced tip speed of 0.63 hover tip Mach number because of operational considerations (the nominal design tip speed of the V-22 Osprey aircraft is $M_{tip} = 0.71$). All airplane-mode proprotor data were acquired at 0.59 hover tip Mach number (equivalent to the V-22 aircraft in airplane mode).

Among the most important information acquired during the TRAM DNW isolated rotor test was the high-fidelity acoustic data from the 1/4-scale V-22 rotor. The acoustic data were acquired using a combination of in-flow traversing and out-of-flow fixed microphones. Thirteen microphones were equally spaced on a traversing microphone wing (also shown in Fig. 4). In addition, two microphones were placed outside the test section flow, one above the model and another located adjacent to the hub on the advancing side of the rotor.

Acoustic data were acquired for a range of advance ratios (μ=0.125, 0.15, 0.175, 0.2), rotor shaft angles (α_S= -14 to +12 deg) and thrust sweeps (C_T=0.009 to 0.014). A detailed discussion of the 1/4-scale V-22 TRAM acoustic results can be found in Ref. 5.

Figure 5 is a representative contour plot of BVI acoustic data acquired with the acoustic survey in helicopter-mode operation. The contours represent 2 dB differences in BVISPL (Blade Vortex Interaction Sound Pressure Level), a noise metric defined as the acoustic energy between the 7th and the 50th blade harmonics. Prominent in Fig. 5 is the BVI 'hot spot' (marked with an 'X') on the advancing-side of the rotor.

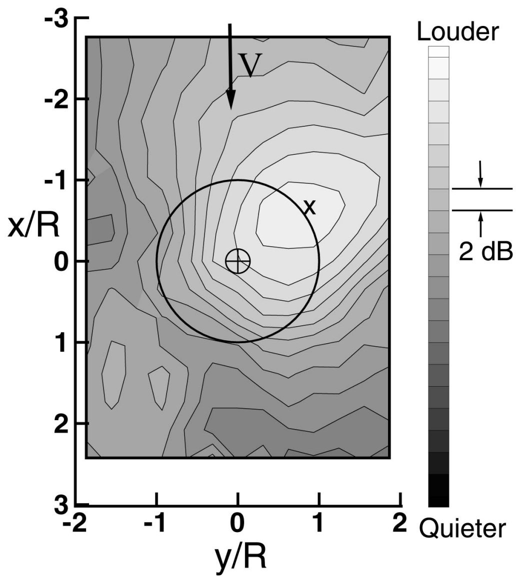
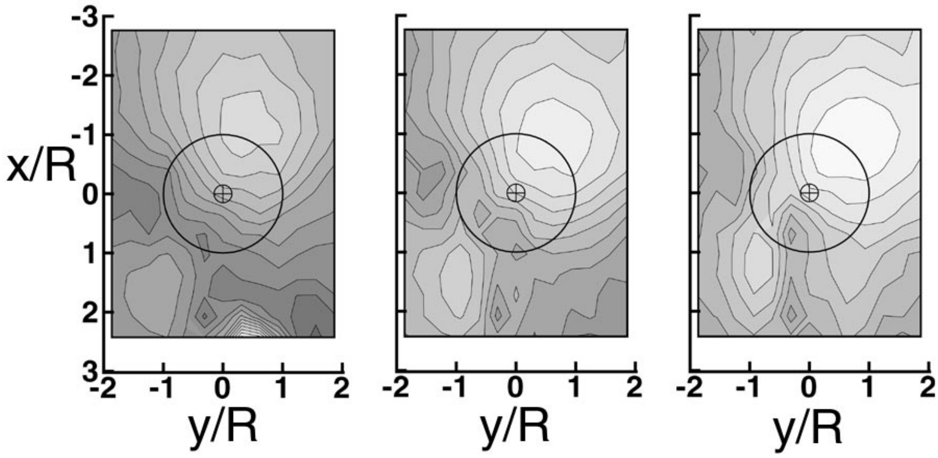


Figure 5. Acoustic survey of proprotor in helicopter-mode (BVI descent condition)

One example of the BVISPL acoustic trend with increasing advance ratio, for constant α_S and C_T, is presented in Fig. 6. As expected, the maximum noise levels increase with increasing advance ratio.



(a.) $\alpha = 4.4^o$, $\mu = 0.15$ **(b.)** $\alpha = 4.9^o$, $\mu = 0.175$ **(c.)** $\alpha = 5.0^o$, $\mu = 0.20$

Figure 6. BVISPL directivity trend with increasing rotor advance ratio

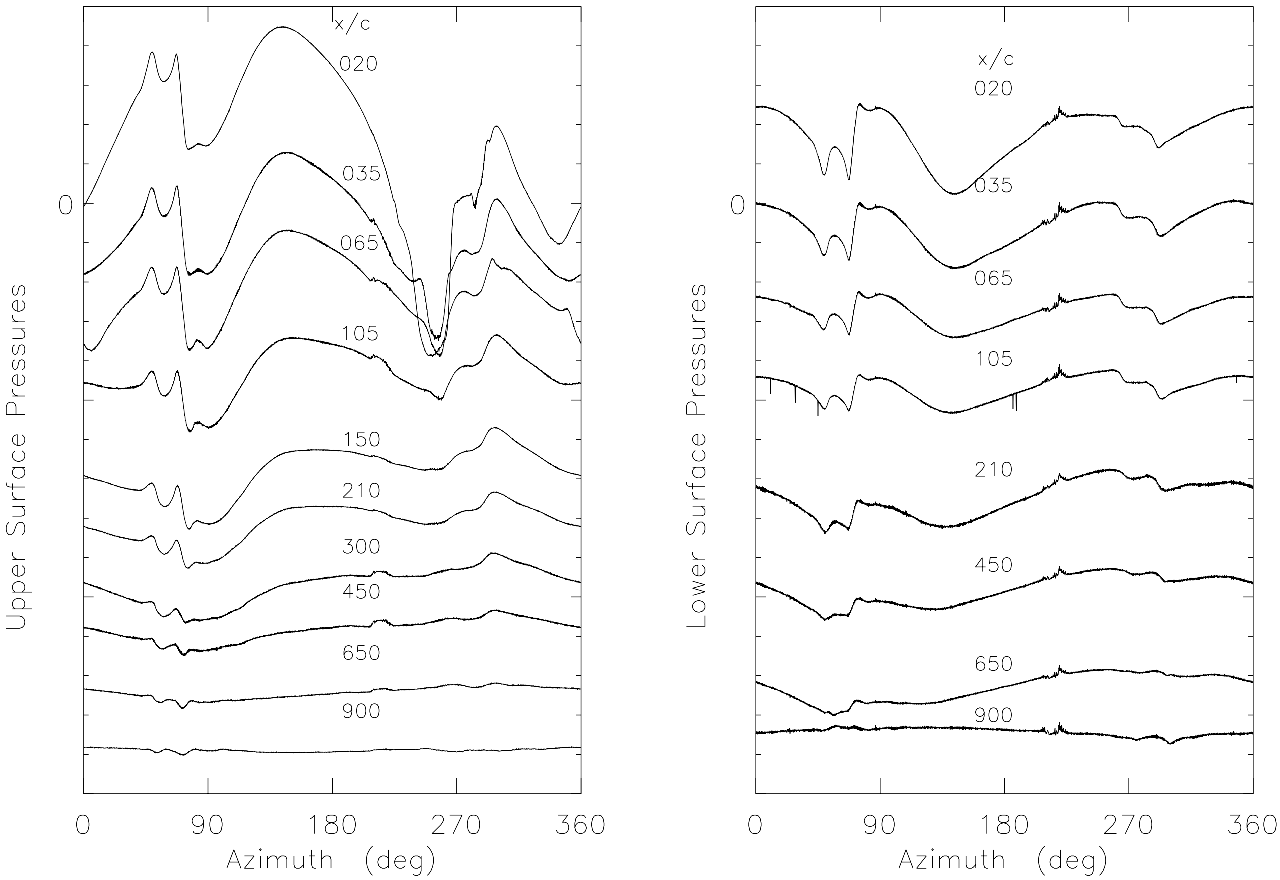


Figure 7. Sample TRAM DNW blade pressure data at r/R = 0.93

Figure 7 represents a very limited sample of the over seventy-five gigabytes of high-fidelity airloads data acquired during the test. A detailed description of the blade pressure data and

analysis of these results will be presented in Ref. 6. The airloads data, which will provide new insights into tiltrotor noise mechanisms, will be an important validation data set for a new generation of aeroacoustic prediction tools and will hopefully inspire new noise reduction strategies for tiltrotor aircraft.

Laser light sheet (LLS) flow visualization and 3-D vortex trajectory measurements were made for the 1/4-scale V-22 rotor. Two-dimensional vortex velocity measurements, using the particle image velocimetry (PIV) technique, were also acquired. Figure 9 is a representative laser light sheet flow visualization image. The rotor blade position is ψ=45 degrees, at μ=0.15 and the visible vortices are on the advancing-side of the rotor.

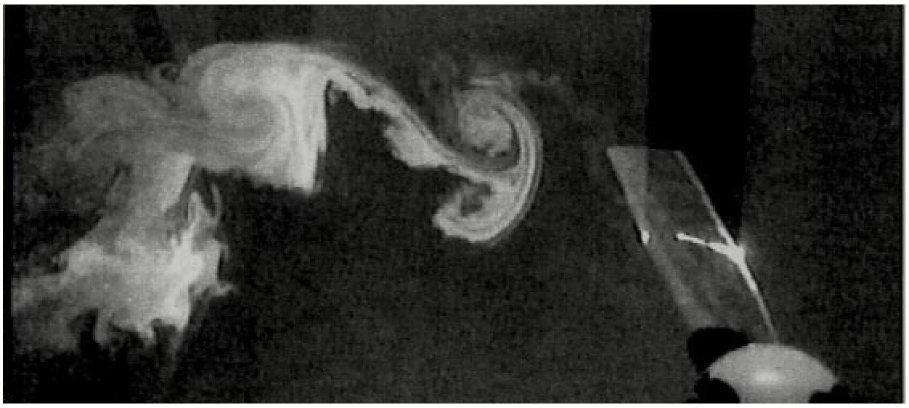


Figure 8. Laser Light Sheet Flow Visualization of Trailed Tip Vortices

Acquisition of a series of laser-light sheet pictures enabled the determination of the three-dimensional vortex filament trajectories on the advancing-side of the rotor. Both clockwise (negative circulation) and counterclockwise vortices (positive circulation) were observed in the laser-light sheet pictures. The rotation directions of the observed advancing-side vortices can be seen in Fig. 8.

Reference 7 presents additional flow measurements findings from the DNW test with respect to the LLS images, the vortex trajectories, and PIV results. One important observation made during the DNW test was the confirmation of paired (one positive, one negative) vortices present on the advancing side of the proprotor in BVI descent conditions.

The TRAM DNW isolated rotor tests were successful in obtaining comprehensive acoustic and airloads data for the 1/4-scale V-22 rotor. The DNW data will enable substantial improvements in the predictive capability for tiltrotor aircraft.

The Future: Full-Span TRAM Testing

After the completion of the TRAM isolated rotor tests, the model was returned to NASA Ames Research Center for refurbishment and integration into the full-span TRAM. The development

of full-span TRAM is well underway and plans are for completion of dual-rotor operational checkout by the end of this year. When model development is completed, the full-span TRAM will support the goals of understanding the interactional aeroacoustics of tiltrotor aircraft and demonstration of potential noise reduction technologies.

Due to three-dimensional unsteadiness observed in the ‘fountain flow’ it is believed that some tiltrotor acoustic sources can only be studied with a full-span dual rotor model (Ref. 8). Studying the noise generating mechanisms and directivity characteristics of these three-dimensional phenomena will be possible with full-span TRAM.

The 1/4-scale V-22 pressure instrumented rotor will be tested on the full-span TRAM in the NASA Ames 40- by 80-Foot Wind Tunnel in late 1999. Figure 9 shows the full-span TRAM model being assembled. The test section of the 40- by 80-Foot Wind Tunnel has recently been modified with a new acoustic liner which is designed to have a minimum of 90% acoustic energy absorption from 80 Hz to 20 kHz (Ref. 9).

Figure 9. Full-span TRAM assembly and functional testing

Two microphone survey arrays will be placed under the model on both sides of the full-span TRAM to assess asymmetric effects and to study rotor-on-rotor -- as well wing-on-rotor -- aeroacoustic influences. Flow conditions tested during the isolated rotor test will be matched to the full-span model testing for correlation and comparison purposes. Figure 10 shows a comparison between the survey area for the DNW isolated rotor tests and the planned full-span TRAM V-22 rotor test planned for the 40- by 80-Foot Wind Tunnel.

The majority of the test matrix for the full-span TRAM will include helicopter-mode and transition testing conditions at full tip speed (M_{tip} = 0.71) for a range of shaft angles and forward speeds. Airplane mode data will also be collected. As with the isolated rotor test, acoustic data, airloads, and flow measurements (both LLS and PIV) will be acquired. Plans are also underway to include the acquisition of wing and fuselage pressure measurements.

Full-span TRAM testing will provide the ability to make comparisons between isolated rotor and dual-rotor with airframe in order to assess interactional aerodynamic and aeroacoustic effects.

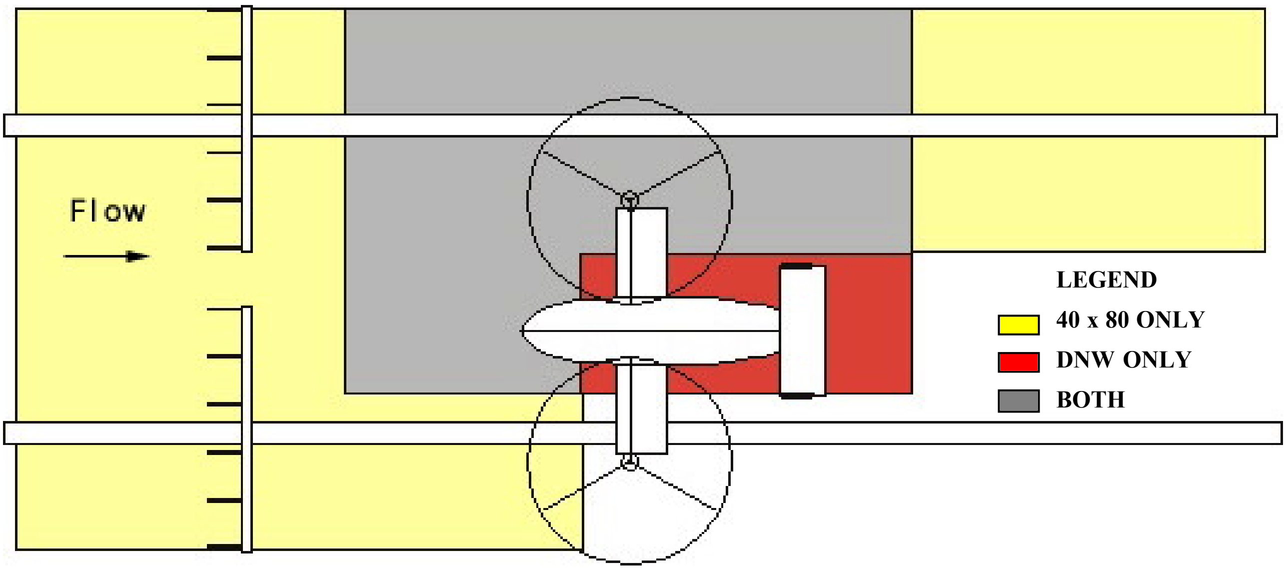


Figure 10. Comparison of acoustic survey area for the isolated rotor vs. full-span TRAM tests

Conclusion

NASA and the U.S. Army have made a major infrastructure investment in tiltrotor test technology through the continuing development of the TRAM. This investment has begun to payoff through acquisition of fundamental aeroacoustic and aeromechanics data from a 1/4-scale V-22 isolated rotor tested in the DNW on the TRAM isolated rotor configuration. The isolated TRAM rotor data will provide much needed insight into the tiltrotor aeroacoustic problem and enable substantial improvements in the predictive capability for tiltrotor aircraft.

Test preparation is currently underway to assess the key interactional aerodynamics and acoustic effects with the TRAM full-span model. The TRAM will provide a wind tunnel demonstrator platform for future tiltrotor noise reduction technologies. Additional in-depth tiltrotor experimental investigations with the full-span (dual-rotor and complete airframe) TRAM configuration are planned in the near future.

Acknowledgments

The work reported in this paper was performed under the auspices of the Tilt Rotor Aeroacoustic Model (TRAM) Project and the NASA Short Haul Civil Tiltrotor program [SH(CT)]. The TRAM and SH(CT) programs are managed at NASA Ames Research Center by the Army/NASA Rotorcraft Division and Advanced Tiltrotor Technology Project Office,

respectively. Other major funding partners and research participants in the experimental research effort were the U.S. Army Aeroflightdynamics Directorate (AFDD) located at Ames, NASA Langley Research Center Fluid Mechanics and Acoustics Division and The Boeing Company (Mesa, Arizona). In addition, the outstanding support provided by the Duits-Nederlandse Windtunnel staff during the execution of the wind tunnel test was critical to the success of the test.

The authors wish to thank Dr. Gloria Yamauchi for contributions to this paper. The authors also wish to acknowledge the dedication and hard work by all members of the TRAM Development and TRAM DNW test teams.

The TRAM DNW test team also extend their thanks to the staff of the Dutch Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), and U.S. Army European Research Office (ERO) for their technical and programmatic contributions to the TRAM development and the DNW wind tunnel access, respectively.

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Appendix – Descriptions of the Isolated Rotor and Full-Span TRAM

TRAM can be configured as an isolated rotor model or as a full-span, dual rotor aircraft model. The rotors and airframe are based on a 1/4-scale of the V-22 Osprey tiltrotor aircraft. The following sections describe the isolated rotor model, the full-span dual rotor model, and components and systems common to both configurations. These common components include the blades, hub, transmissions and drive shaft components, rotor balance and rotating amplifier system.

Isolated Rotor Configuration

The TRAM isolated rotor test stand is comprised of two major elements: the rotor and nacelle assembly and the motor mount assembly. The rotor and nacelle assembly is attached to the acoustically treated isolated rotor test stand at a mechanical pivot or 'conversion axis' (Fig. 2). This conversion axis allows the nacelle to be manually rotated in 5-degree increments from airplane to helicopter mode.

The isolated rotor test stand drive train arrangement is shown schematically in Fig. A1.

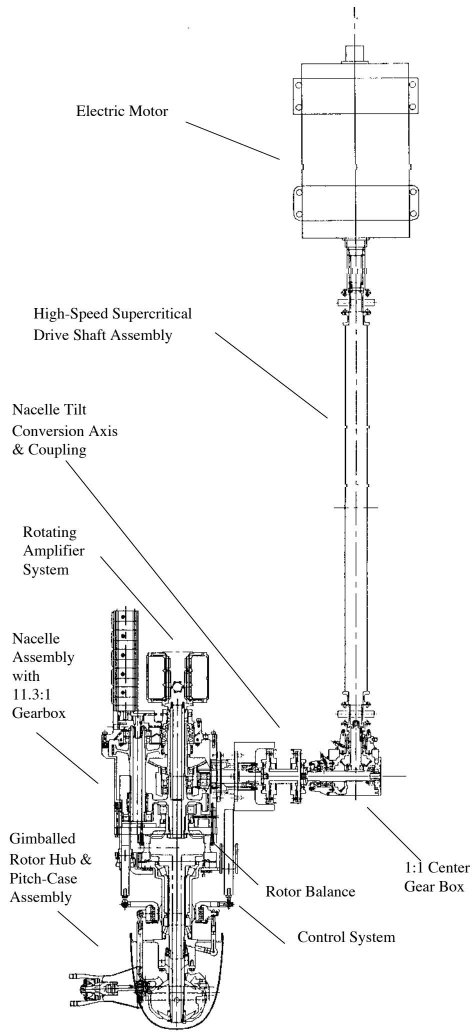

Figure A1. Schematic of the TRAM isolated rotor configuration and key sub-systems

An electric motor provides power to the rotor via a super-critical driveshaft and two gearboxes. The nacelle assembly contains a reduction gearbox that reduces speed by 11.34:1. The case of the nacelle gearbox is designed to carry the structural loads of the rotor through the conversion axis to the model support. Rotor shaft angle changes are accomplished during testing by pitching the entire test stand using the wind tunnel sting pitch mechanism. During the isolated rotor test, the DNW sting automatically maintained the hub on tunnel centerline as the model was pitched. The motor mount and model support assembly is acoustically treated with foam panels. The nacelle assembly is not acoustically treated but is geometrically scaled to the V-22 aircraft.

Full-Span TRAM Description

The full-span TRAM basic model consists of a steel and aluminum frame with fiberglass skins, a steel wing and an aluminum empennage, and dual rotors. The wing was not designed to be aeroelastically scaled with respect to the V-22 aircraft. The model structure is designed for testing up to 300 knots (maximum speed of NFAC). The full-span TRAM is equipped with remotely adjustable flaperons and one elevator. The rudders are ground-adjustable but are nominally zero degrees for most wind tunnel testing. The wind tunnel mounting strut and the

tunnel turntable provide angle-of-attack and yaw control. Nacelle tilt settings on the full-span TRAM are accomplished manually, as on the isolated rotor configuration. The left-hand wing and flaperons are currently being modified to include chordwise distributions of static pressure taps at five wing span locations. Figure A2 shows the major components of the full-span model.

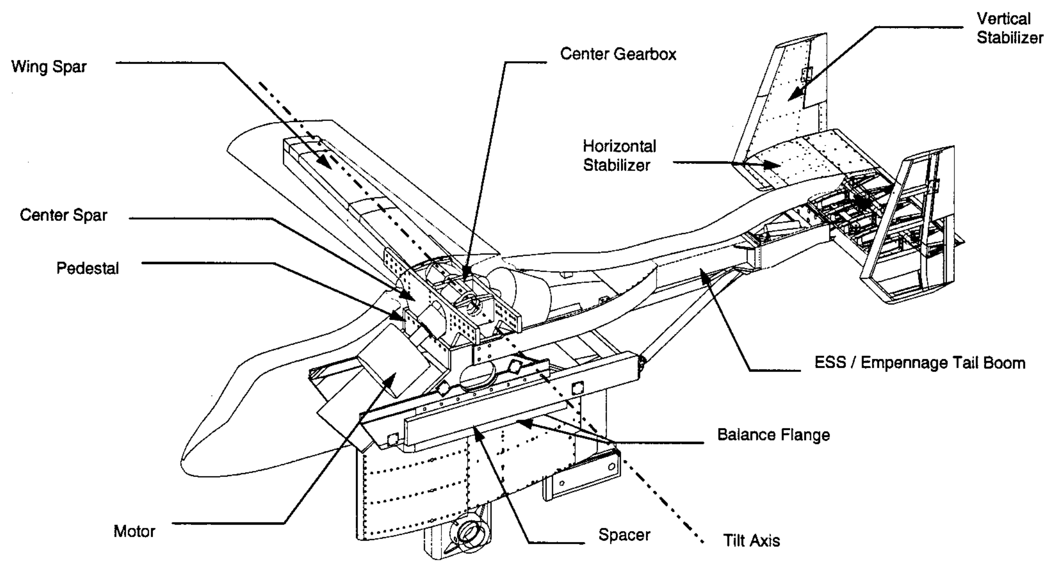

Figure A2. Full-span TRAM components

One of the unique features of the full-span TRAM (as compared to the isolated rotor configuration) is a fuselage balance that measures the total model aerodynamic loads. This fuselage balance is a six-component strain-gauged balance located in the fuselage. The fuselage balance maximum design loads are provided in Table A1.

Table A1. TRAM fuselage balance design limits

	Design Limit
Thrust Force	+4000, -8500 lbs.
Side Force	±1500 lbs.
Drag Force	+2000, -6000 lbs.
Pitch Moment	+100,000, -150,000 in-lbs.
Roll Moment	± 35,000 in-lbs.
Yaw Moment	±40,000 in-lbs.

Two tandem mounted high-speed electric motors are housed in the fuselage and a series of gearboxes and drive shafts transmit power through the wing into transmissions in the nacelles. The motors and drive train are designed to deliver up to 300 HP to each rotor. Similar to the isolated rotor configuration, each nacelle contains a gearbox to reduce the speed and transmit power to the rotor hub. The purpose of the TRAM drive train is to transmit power from the two electric motors in the fuselage, through the wing, to the nacelle mounted rotors. All of the components from the motors to the input of the nacelle transmission are designed to operate at

18,000 rpm. The center-mounted gearboxes are 1:1 right angle transmissions that turn the drive train into the wings. These two gearboxes are connected together so the two rotors are mechanically linked for safety, similar in purpose to the cross-shaft in the wing of the full-scale aircraft. The drive shafts in the wing are designed to operate above their first fundamental frequency of approximately 6600-rpm. A flail damper system is incorporated at the shaft mid span for safety in case the shaft deflection goes divergent during transition through the critical speed. The supercritical drive shafts are supported on each end by dual-diaphragm couplings. These couplings are designed to permit angular deflections up to four degrees at 18,000 rpm. The angular deflection is required to accommodate the wing dihedral and nacelle cant angles, the combination of which result in an approximately 3.5 degree coupling deflection. The nacelle transmission has three stages of gear reduction which combine to reduce the 18,000-rpm input to 1588-rpm output (11.34:1).

The two electric motors are solid-state controlled permanent magnet motors providing each rotor with 300 HP at 1588 rpm. Although this level exceeds 1/4 scale V-22 power requirements, extra capacity was designed into TRAM for future testing. These power requirements, combined with the relatively small space available in the 1/4 scale model, dictated that the motor and a large portion of the drive train operate at 18,000 rpm. This speed is necessary to transmit the required power, with adequate safety margins, through the 1/4 scale wing to the rotors. A transmission in the nacelle is then required to reduce speed to 1588 rpm at the rotor. This rotor speed for the TRAM matches the full-scale aircraft tip speed of 0.71 ft/s. The TRAM electric motors are based on a unique permanent magnet design in combination with advanced high-speed PWM (pulse width modulated) switching technology for motor control. This approach allows for high power capability in a package small enough to fit inside the TRAM fuselage. Figure A3 shows one of the electric motors.

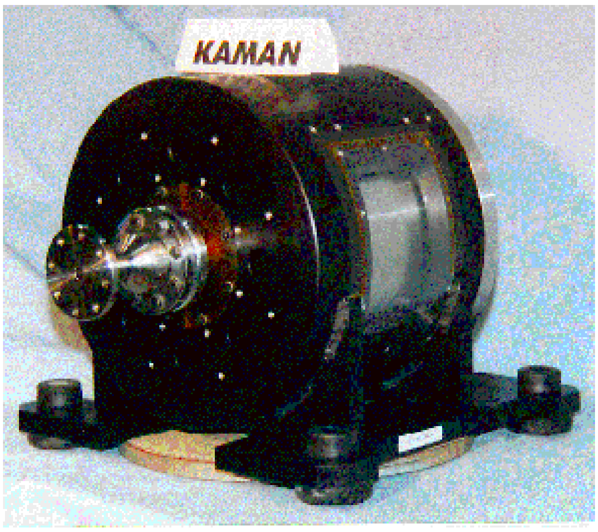

Figure A3. TRAM electric motor (one of two required to power full-span TRAM)

Over 700 data, health monitoring and 'Safety-of-Flight' (SOF) instrumentation channels are incorporated into this model. Health and SOF monitoring systems, utility and fixed-wing control console workstations were developed to support efficient and safe wind tunnel testing.

The right-hand rotor hub and control system, blades, rotor balance, rotating amplifier system and slipring are the same components used in the isolated rotor model and will be described in the following sections. The corresponding left-hand components (except for the rotating amplifier system and slipring) are mirror images of the right-hand components.

Components Common to the Isolated Rotor Configuration and the Full-Span TRAM

Rotor Hub and Control System

The TRAM baseline gimbaled rotor hub incorporates a constant velocity joint (spherical bearing and elastomeric torque links) and is dynamically and kinematically similar to the V-22 aircraft. The rotor control system is comprised of three electromechanical actuators, a rise-and-fall swashplate, and rotating and nonrotating scissors allowing full proprotor collective and cyclic control. A remotely mounted rotor control console allows pilot inputs to be made from the wind tunnel control room. The two rotors can be controlled independently or linked-together. Figure A4 shows a schematic of the TRAM hub.

Rotor Blades

The composite-material rotor blades have both strain-gauge and pressure transducer instrumentation. The rotor diameter is 9.5 feet (2.9 m). All blades, whether strain-gauged or pressure-instrumented, have the same mass distribution properties and can be readily interchanged per rotor. The blades have high fidelity scaling with respect to the V-22 rotor for blade/airfoil contours. Additionally, the first elastic modes (flapwise, chordwise, and torsional) of blades were dynamically scaled to V-22 aircraft frequencies.

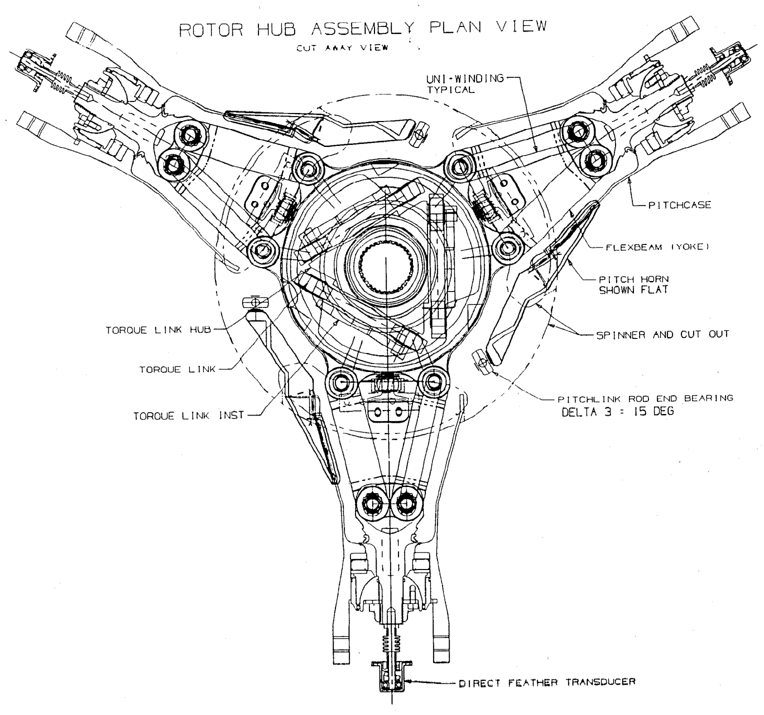

Figure A4. TRAM hub schematic

Two blades of the right-hand rotor blade inventory are pressure-instrumented. Three right-hand strained gauged blades were fabricated so that researchers have a choice of two right-hand rotor

sets: 1) a pressure-instrumented set consisting of two pressure-instrumented blades and one strain-gauged blade, or 2) a set made up of three strain-gauged blades. The left-hand blade inventory consists of only strain-gauged blades (three plus one spare). Each strain-gauged blade was fabricated with 14 strain gauge (full-bending) bridges installed: five flapwise bending-moment, five chordwise bending-moment and four torsion.

Rotor pressure-instrumentation consists of 150 dynamic transducers distributed over two rotor blades on the right-hand rotor only. The transducers are flush-mounted with a pressure range of 25 psi absolute. Three transducer model types were installed: pipette, B-screen, and flatpack. All transducer types have the same electrical specifications with a vendor-quoted, flat-response characteristic of less than 0.5 dB out to 60 kHz. Figure A5 shows the distribution of the transducers over the two blades.

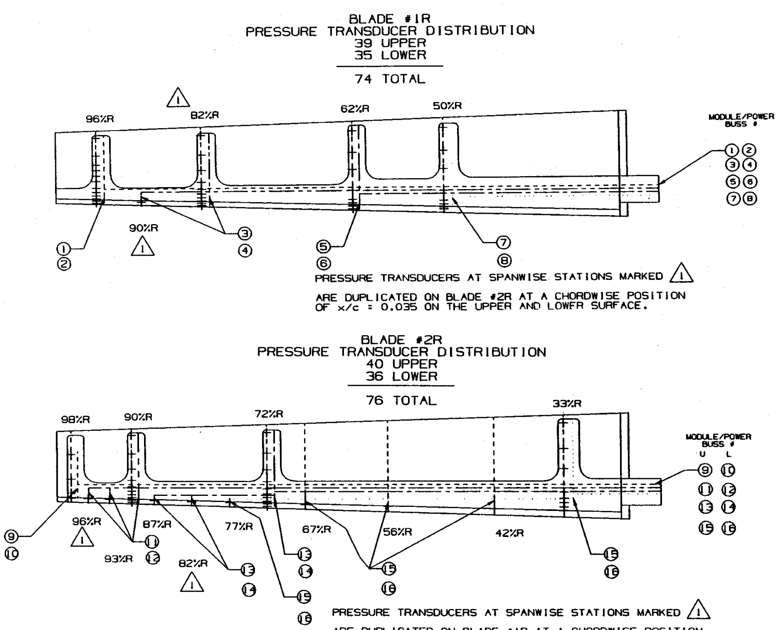

Figure A5. Pressure-instrumented blade transducer locations

Rotor Balance

The full-span TRAM incorporates two identical six-component strain-gauged balances, one in each nacelle. The TRAM isolated rotor configuration uses one of the two rotor balances. The balance design is comprised of four strain-gauged posts instrumented with primary and backup sets of gauges, which allow the measurement of the rotor aerodynamic forces and moments. A flexible coupling provides transmission of torque to the rotor hub through a load path independent of the rotor balance. Therefore, this coupling is instrumented to measure torque and any residual thrust carried by the drive system. Data reduction software corrects the rotor balance thrust measurement for this residual thrust component.

The rotor balances incorporate a fail-safe retention design. In the event a balance flexure breaks the rotor is captured. A heater system is integrated into each rotor balance. Heater coils on metric and non-metric sides are close-loop controlled to maintain constant balance temperature during a data acquisition run in the tunnel. Each flexure has eight thermocouples installed to record the rotor balance distributed temperature characteristics during a run. The rotor balances are mounted in the model with ceramic insulators on both the metric and non-metric sides to stabilize the heat transfer throughout the balance. The base of the rotor balance is mounted to the nacelle transmission (non-metric side) and the static mast is mounted to the metric side of the balance. The rotor balance maximum design loads are provided in Table A2.

Table A2. Rotor balance design load limits

	Design Limit
Thrust Force	+3000, -500 lbs.
Side Force	+750, -750 lbs.
Drag Force	+750, -750 lbs.
Pitch Moment	± 2400 in-lbs.
Roll Moment	± 2400 in-lbs.
Yaw Moment	N/A
Torque*	+15,600 in-lbs.

*Torque measured by flex coupling, rotor balance yaw moment is the residual torque.

Rotating Amplifier System (RAS) and Slip-Ring Assembly

All rotating data channels were amplified by a rotating amplifier system (RAS) developed by the Nationaal Lucht-en Ruimtevaartlaboratorium (The Netherlands National Aerospace Laboratory, NLR) to enhance transducer signal-to-noise ratios before entering the slipring (Ref. 10).

Early in TRAM development, it was anticipated that the blade pressure transducers would be susceptible to electromagnetic interference (EMI) noise from the model's electric drive motors and from passing the signals from the rotating frame, through sliprings, to the non-rotating side of the model. In order to mitigate the effect of these noise sources on blade pressure data quality, a compact precision amplifier system was developed to boost the signal levels in the rotating frame prior to passing the signals through the slipring. Another advantage of a rotating amplifier system is the reduction in the number of rings in the slipring since the amplifier converts each channel to single-ended output. The RAS was designed to provide signal conditioning and amplification of 256 channels and to provide up to 128 unmodified or ‘pass-through’ channels. The pass-through channels are used for safety-of-flight monitoring of critical blade and hub structural components.

The entire RAS system is contained in a cylindrical housing 7.0 inches (178 mm) in diameter and 5.6 inches (142 mm) in height. The RAS cylindrical housing is divided into 16 ‘pie’ shaped modules each containing 16-hybrid amplifier cards. The RAS design utilizes hybrid circuitry to perform signal conditioning and amplification; the hybrid circuitry minimizes the size of each

amplifier card. Photographs of the RAS modules, housing and hybrid amplifier cards are shown in Figure A6. Each card has four selectable gain and three resistor calibration (Rcal) settings. The settings are programmable via an RS 232 link to a PC. Software has been developed to permit adjustment of the gain settings during a wind tunnel run to permit maximum signal resolution for each test condition.

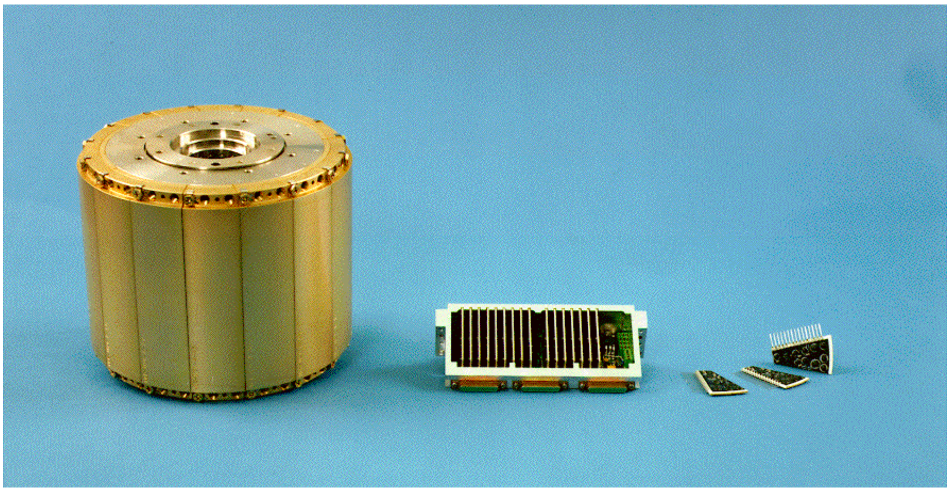

Figure A6. Photograph of RAS and components